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Systematic Integration of Design-for-Recycling into Product Design

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This paper presents an approach for incorporating recycling considerations into product design. The approach regards the recycling aspects of product design, different recycling processes and the product logistic support during the end-of-life stage. The concept of a recycling network is introduced which consists of the designer, consumers, recyclers and suppliers, allowing the effective exchange of information and handshaking for cooperation. Guidelines dedicated to design-for-recycling are presented to assist the designer to develop a recycling friendly product reflecting the objectives of all network partners. The approach is demonstrated by investigating current industrial product recyclability features and further improving them by applying design-for-recycling guidelines.

1. INTRODUCTION

Environmental issues are becoming increasingly important to product designers and manufacturers. Public awareness of the value and fragility of an intact ecology constantly increases and the traditional assumption that the cost of ecological burdens is to be shared by the society as a whole is no longer acceptable. For example, last year (1993), the European Union introduced a set of guidelines, the Eco Management and Audit Scheme (EMAS), which, although still voluntary, has signaled that environmental responsibility should lie with industry. In Germany this attitude is already enforced through legislation guided by the originator-principle (Verursacherprinzip): "He who inflicts harm on the environment should pay for fixing the damage".

This trend is most apparent when considering the environmental impact of worn-out products. The shortage of landfill and waste burning facilities constantly reminds us that our products do not simply disappear after disposal. It is currently widely acknowledged that the most ecologically sound way to treat a worn out product is recycling. Since it is rarely possible or beneficial to recycle a product completely, the aim is to maximize the recycled resources while minimizing the effort that has to be invested. This balance must be observed while taking economic factors and other societal factors into account. The multi-objective goal which we term end-of-life value can be realized by two means: Improvement of recycling processes by developing more sophisticated recycling technologies (e.g. advanced separating and purifying methods), and improvement of product design in a recycling-friendly matter. It is widely believed [1] that only 10-20% of recycling costs and benefits depend on recycling process optimization. The remainder is already determined at the design stage. Hence it is an industry wide interest to develop methods and tools for incorporating environmental considerations into product design.

A number of works addressing this problem have been published. Of major importance are those works which can be broadly labeled the life-cycle analysis approach. The idea is to explore the different product's life-cycle phases including the

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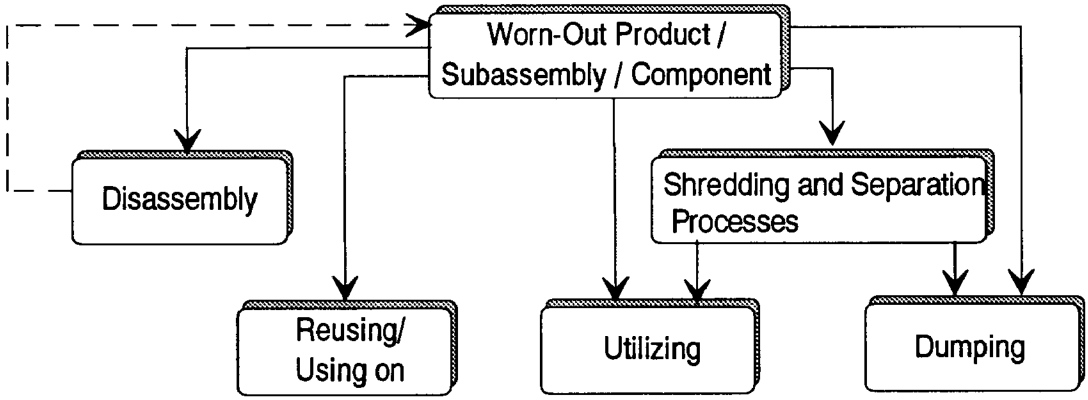

Figure 1. Recycling options at the product's end-of-life stage.

end-of-life phase. Different paradigms are presented in [2,3,4,5,6] where the integration of recycling considerations is suggested. Other works present design-for-recycling guidelines for specific type of products [7,8] or for general products for helping the designer to assess, compare and to make design decisions [9,10,11,12,13,14,15,16].

The work presented here aims at extending the above by supplying the designer with a set of information tools and structured design guidelines for integrating end-of-life aspects into the product design. We suggest a system approach, in which product, production and logistic support life-cycles are planned simultaneously in order to observe all relevant recycling parameters.

The paper is organized as follows: The following section deals with the current understanding of recycling and the developments in recycling technologies. In section three we present a method for systematic integration of recycling considerations into product design. We show how the recycling demands and activities influence the life-cycle of the system. The fourth section presents the recycling network concept and the information flow among the different functions. In section five we detail the aspects of design-for-recycling emphasising guidelines and procedures to improve product recycalability. Finally a case study is given describing the current recycling features of a washing machine subassembly and how applying design-for-recycling guidelines can improve its recyclability.

2. RECYCLING OPTIONS

Recycling aims at "closing the loop" of materials and components after usage by (re)using/utilizing them for new products. Three loops can be distinguished in a product life-cycle, during which recycling activities can take place [17,18] :

- Recycling of production scrap - utilizing residues of manufacturing processes, e.g. from punching, injection moulding.
- Recycling during product usage - continued use of a product after repair or remanufacturing.
- Recycling after product usage - recycling at the end-of-life stage which is the topic of this investigation.

During the loops, different forms of recycling are possible. Keeping the shape of the original product for future tasks is defined "using", while making use of the material after dissolving the original shape is called "utilization". If the function of the recycled product is the same as the one of the original product, we speak of "reusing", otherwise of "using on".

At the end-of-life stage of complex products (e.g. household appliances, cars), different recovery operations precede recycling (fig. 1). We distinguish two types of recovery operations:

- Disassembly - decomposition into subassemblies or components while keeping their original form.
- Shredding and separation - decomposition into random minute pieces which are then separated by different means.

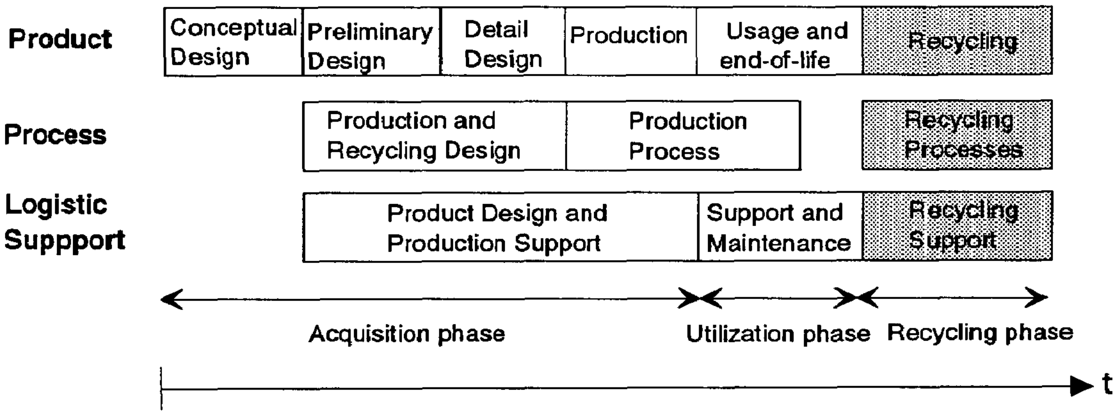

Figure 2. System life-cycle.

Dumping of a product, or residues of it, is also considered as a possible option for a product end-of-life while considering the level of toxicity of the dumped material.

3. RECYCLING CONSIDERATIONS IN THE SYSTEM LIFE-CYCLE

Ecological orientation is not limited only to production and marketing. The entire product life-cycle must be considered. However, in addition to extending the time horizon there must also be a broadened approach in another dimension. Besides the environmentally friendly composition of their products, companies have to consider the environmental impact of the processes and of the logistic support. Therefore, an integrative approach is desired which considers these three elements during the whole life-cycle. Such an approach is denoted here as a system approach and is represented in this section with emphasis on its recycling aspects.

A system is defined as an assemblage or combination of elements or parts forming a complex [19]. All relevant interdependencies and interactions must be enclosed. A product in general cannot function properly without an operator, a production system, a support capability, and so on. Therefore, when companies adopt the system approach, not only the product must be considered, but its production process, usage, its maintenance capabilities, support, and recycling options. Proper functioning and competitiveness of such a system can not be achieved through efforts applied largely after the product's design stage. Especially, the ecological aspects are the ones that must be planned in advance and considered in order to form an ecologically sound system.

The system presented here includes the life-cycles of three elements: the product, its related processes, and its logistic support (fig. 2). These three life-cycles should be considered simultaneously while following the system life-cycle during the acquisition, utilization, and recycling phases.

- *Product life-cycle* - the product life-cycle begins with the identification of the needs and extends through design, planning, production, assembly, usage, end-of-life and recycling stages. For the recycling, the most influential phase is the design. It determines the recycling options of the product and influences the options for recycling processes, as well as the logistic support during the end-of-life stage.
- *Process life-cycle* - the process life-cycle begins with the definition of the production task by the product design. It encloses the design of the production and recycling systems and processes. With regard to recycling, production process planning has to deal with minimizing production waste and finding ways to recycle it. As to the recycling system, the aim is to find the processes which lead to the maximum end-of-life value, namely, regaining components, materials and

energy for further use while minimizing recycling efforts.

- *Logistic Support life-cycle* - the logistic support life-cycle encloses the support during the design and production stages, the consumer support and maintenance during the product usage, and the support for the product recycling. Of interest to the recycling are the collection and transport of used products, providing product information (e.g. materials composition) for the recycling industry and possibly transferring used materials and components back to the production of future products.

4. THE RECYCLING NETWORK

Addressing the environmental problems in the context of the system life-cycle requires rethinking long-standing business relationships of the manufacturers with suppliers and consumers. They must establish cooperative relationships with suppliers, consumers as well as recyclers in order to manage materials flow in an environmentally sound way. To provide the necessary communication infrastructure and to support collaboration and coordination needs we propose here to form a recycling network. It should consist of a "server" which is the designer and "clients" representing the consumers, recyclers and materials/components suppliers (fig. 3).

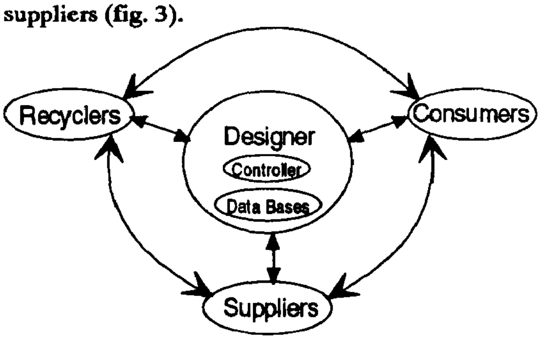

Figure 3. A recycling network.

In this network the recyclers are considered as dismantlers and waste management providers. The function of recyclers can be provided by the original product manufacturer, an independent recycler, or what is widely common today, a contract recycler which recycles products for a manufacturer who retains ownership of the products. Suppliers have to honour the requirements of the designer to use recycled materials provided by the recyclers. The designer as a "server" controls the network and provides the "clients" with recycling data and assessments of the different decisions [15].

The recycling network acts along the life-cycle of the system and provides the relevant information at each phase. Starting at the conceptual design stage the network allows designers to represent and communicate pertinent information about the candidate design. The network allows exchange of information on monetary and environmental issues and an access to environmental databases providing information on legislation, materials, recycling processes and product history. Conflicts arising during product design (e.g. materials compatibility for recycling) can be resolved since the different network partners can make informed decisions collaboratively.

In many cases, information exchange via networks can play a decisive role in shaping design solutions resulting in significant environmental improvements. Cooperating in the recycling network can help to improve design for recycling. Designers will, in addition, provide the recyclers with knowledge on how to recover the materials and components and thus improve the effectiveness of recycling processes. Moreover, designers will have the option to control the material loop, either by encouraging their material suppliers to accept recovered materials from the recyclers, specifying the exact properties of the recovered materials, or by creating markets for their own recycled materials through setting up special purchasing programs.

We identified different messages in the network which are of relevance to the end-of-life stage:

Designer /Recycler

- Ways of collecting, transporting and storing the product after usage.
- Available recycling methods.
- Markets for materials.
- Information on material properties for ease of sorting and separation.
- Information regarding the existence and location of reusable components, valuable or harmful

materials as well as process information, i.e. hints for the most effective disassembly plan.

Designer / Consumers

- Tracking of products in management of service and maintenance activities all along the utilization phase. Of importance is to track the exchange of parts of the product during repair or upgrading. Doing so will reduce the product recovery uncertainties.

Designer / Suppliers

- Specification of the use of recovered materials in new parts, or reuse components.
- Markets for materials.
- Properties/Quality of recycled materials and reliability.

5. DESIGN-FOR-RECYCLING

As we have shown, the designer plays the key role in improving the recyclability of products. He has to take into account the requirements of recycling processes that may lie 15 to 20 years ahead. In general this problem is difficult even for experienced designers and cannot be formalized into an efficient algorithm. As there are no formal rules for design-for-recycling, we resort to heuristics. We provide the designer with a set of guidelines, that are simple, easy to apply and easy to evaluate in the network framework. A possibility to structure these rules is to form groups of rules relating to some design aspects as following [16,18]:

1. *Criteria regarding individual components:*
- Avoid hazardous and otherwise environmentally harmful materials.
- Avoid materials and components incompatible with standard recycling processes.
- Prefer materials that can be reutilized easily.
- Allow for the reuse of recycled components.

2. *Criteria regarding subassemblies:*
- Cluster materials with respect to utilization compatibility.
- Allow for the use of recycled subassemblies.

3. *Criteria regarding disassembly operations:*
- Use joining elements that are easy to disassemble between subassemblies consisting of incompatible materials.
- Design easily accessible joining elements.
- Use joining elements that do not require special tools.
- Protect joining elements from corrosion and wear.
- Avoid the need of destructive disassembly techniques if they produce sharp edges.

4. *Criteria regarding the product as a whole:*
- Minimize the variety of materials.
- Minimize the number and variety of joining elements.
- Make harmful/valuable components/materials easily accessible.
- Avoid precedence relations between parts.

5. *Criteria relevant to logistic:*
- Provide information relevant to recycling: material content, disassembly procedures, available recycling options and processes, etc.
- Design the product in a way that it can be transported easily after usage, i.e. by allowing pre-disassembly.
- Encourage the consumers to begin the recycling process.

All the given rules effect the efficiency of the recycling process. They must be integrated in the conceptual design stage and applied simultaneously with the requirements of manufacturing, maintainability, reliability and other design objectives.

6. A CASE STUDY

As a case study, we demonstrate our suggested approach on a subassembly of a washing machine. At first we aim at evaluating the current recycling situation of the subassembly and in general of washing machines. Further on we show how the requirements of the network partners can be reflected in product design.

The subassembly consists of 4 main components (fig. 4). Its weight is about 7 kg. The material composition is shown in table 1.

After an average life-cycle of 8-12 years washing machines are reaching their end-of-life phase. Generally, machines are deposited at the roadside and collected by the community, forwarded to local refuse sites from where they are either deposited or taken to shredders. A small percentage of machines is collected by local dealers upon delivery of new machines and forwarded directly to shredders. After shredding, the metallic fraction is reutilized and the remainder (plastics, glass etc.) is dumped [20]. Currently, the high cost

Component	Material
Top cover	wood with melamine resin (thermosetting), ABS (thermoplastic)
Metal cover	sheet metal
Detergent drawer	PP (thermoplastic)
Control panel cover	ABS, PC, PMMA, POM, PA, PS (different kind of thermoplastics), lamps, and electronic boards with hazardous material - PCB (polychlorinated biphenyl)

Table 1. The material composition of the subassembly

for collection and transport of the washing machines, relative to difference between the scrap price and the dumping cost is the main obstacle for the limited scale of utilizing this source of materials and components.

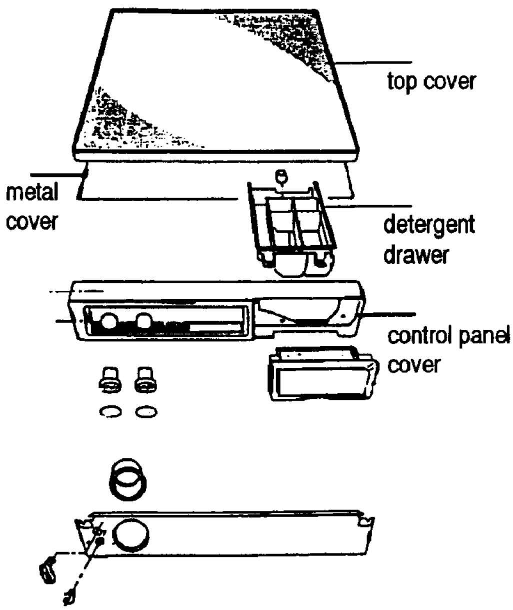

Figure 4. A washing machine subassembly.

Improving the recyclability of the subassembly can be done in several aspects. The following redesign suggestions represent options for new design, use of recyclable materials and applying recovery processes. We follow the design guidelines suggested in Section 5.

Components and subassembly:

- The variety of plastics in the subassembly must be reduced in order to make the separation easier and obtain compatibility among the different kinds of plastics. An attractive solution to material suppliers is to use only ABS, PC, and PMMA (thermoplastics). Although such a material change is not currently cost effective, in future there is likely to be legislation requiring recycling of some proportion of plastics, up to 50% [20]. It is therefore very likely that in the coming years plastics recycling systems will be implemented and markets for recycled plastics developed.
- The elements in electronic boards containing PCB can be replaced.

Recovery by efficient Disassembly:

Disassembly of some parts is recommended for two reasons: To enable reuse as spare parts and to guarantee a high degree of purity for recycling of materials. We found that the following suggestions can improve recycling processes.

- Clustering the electrical/electronic components together so they can be easily disassembled.
- Use special snap-fits to connect the top cover to enable easy disassembly [18].

Logistic aspects:

- The effort required for logistic functions of recycling depends to a large extent on the prevention of destruction during transport while simultaneously reducing the transport cost. The designer can provide information on possible future reuse and reutilisation, defining the components that have to be handled with special care.

  In the given example, the connection of the top cover to the body of the washing machine is a critical point. As the main electronic board is situated directly beneath the top cover, it is advantageous to preserve the connecting screws in order to facilitate easy disassembly.

At the end of the design modification we get better recycling features of the subassembly. The electronic and other electrical parts can be easily disassembled and reused for less demanding applications or as spare parts. The top cover is also disassembled and can be used for energy utilization. The rest of the subassembly can be shredded as a whole. A mixture of these plastics can be used for various applications as an aggregate in polymer concrete applications.

7. CONCLUSIONS AND SUMMARY

Due to the continuing disturbance to our environment, industry is expected to make greater contributions to solving the ecological problems created by their products. Reducing the burden from the ecological system while maintaining the current standards of living requires the development of innovative technologies. An example of such a technology is recycling, aiming at further use of materials and components.

In this paper we present a concept which allows industry to take responsibility for the whole life-cycle of a product starting at the design stage and ending at the recycling stage, while considering the different recycling processes as well as logistic aspects. A recycling network is introduced defining different messages between the recycling system "server" (the designer) and "clients" (consumers, recyclers and suppliers). A set of design-for-recycling guidelines and rules is presented. It can help a product designer to integrate recycling considerations into product design.

Following the above recycling approach via a systematic integration of recycling considerations into a product, companies will be able to comply with legislation, consumers demands and future demands regarding product liability. Taking such an approach requires changing the traditional design, production, and end-of-life phases of the life cycle. In a long term, companies adopting this approach while combining innovative technologies may make the recycling activities profitable.

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